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Testing a Shape-Changing Haptic Navigation Device with Vision Impaired and Sighted Audiences in an Immersive Theatre Setting

Adam J. Spiers, *Member, IEEE*, Janet van der Linden, Sarah Wiseman, and Maria Oshodi

***Abstract*—Flatland was an immersive 'in-the-wild' experimental theatre and technology project, undertaken with the goals of developing systems that could assist 'real-world' pedestrian navigation for both vision impaired (VI) and sighted individuals, while also exploring inclusive and equivalent cultural experiences for VI and sighted audiences. A novel shape-changing handheld haptic navigation device, the 'Animotus', was developed. The device has the ability to modify its form in the user's grasp to communicate heading and proximity to navigational targets. Flatland provided a unique opportunity to comparatively study the use of novel navigation devices with a large group of individuals (79 sighted, 15 VI) who were primarily attending a theatre production rather than an experimental study. In this paper we present our findings on comparing the navigation performance (measured in terms of efficiency, average pace and time facing targets) and opinions of VI and sighted users of the Animotus as they negotiated the 112m^2 production environment. Differences in navigation performance was non-significant across VI and sighted individuals and a similar range of opinions on device function and engagement spanned both groups. We believe more structured device familiarization, particularly for VI users, could improve performance and incorrect technology expectations (such as obstacle avoidance capability), which influenced overall opinion. This work is intended to aid the development of future inclusive technologies and cultural experiences.**

***Index Terms*—Haptics Technology, Assistive Technology, Human Factors and Ergonomics, System Design and Analysis, Navigation, User Interfaces, Blindness**

I. Introduction

In the 19th century novel Flatland [1], geometric characters of lines, squares and spheres inhabit distinct worlds defined by varying numbers of dimensions. In real life, sensory impairments can lead to similar distinctions, with sparse opportunities for 'equivalent' experiences between vision-impaired (VI) and sighted individuals. One key example of this is in the realm of pedestrian navigation, where the avoidance of obstacles and finding/following a route to a target is severely complicated by a lack of vision [2]. Since the 1960s, researchers have investigated the potential of using various technologies to aid perception and navigation for VI pedestrians [3]–[5], yet currently the most ubiquitous navigational devices (smartphones and in-car GPS systems) rely primarily on VI-inaccessible visual displays for interaction, with optional audio stimulus providing potential distractions from environmental cues and hazards [6] (as will be discussed in Section 2.2).

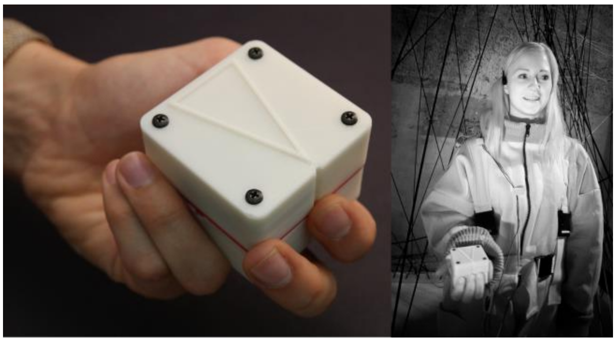

Fig 1: The 'Animotus' shape-changing haptic navigation device (left). Each audience member (right) used an Animotus to navigate the pitch-black Flatland production.

Beyond technology, cultural works (such as film, theatre or curated galleries) are sometimes modified to form 'VI-accessible' versions to enable accessibility to wider audiences. However, these efforts are often 'retro-fitted' editions of materials designed and produced for sighted audiences, with audio narration aiming to substitute visual stimulus. Unfortunately, audio can only provide a limited representation of such information (compared to a full visual scene) and may again, distract or interfere with the goals and intentions of the original material.

In our work, we seek to explore the potential for subtracting and substituting sensations as a way of designing inclusive technologies and experiences that extend beyond accessibility by being inherently suitable for both VI and sighted individuals. The most recent effort towards these goals was a 2015 production of Flatland, the result of a collaboration between sighted engineers/researchers and a vision impaired theatre

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Fig 2: An audience member in a section of the Flatland environment, showing two of the four tactile set pieces that acted as navigational targets with associated audio narrative. Audio was delivered through bone-conducting headphones and ambient speakers.

company. This led to a fully immersive theatre production within a dark environment that VI and sighted audiences were guided through using a novel haptic navigation device, The Animotus (Fig 1). This device was designed with the intention of presenting a user with highly intuitive, yet unobtrusive, navigation guidance that would not distract from the overall dramatic experience. We consider such a goal of low cognitive distraction as also beneficial for urban navigation, where increasing numbers of accidents result from pedestrian distraction by smartphone devices [7]–[10]. These considerations led to a novel interface modality choice of haptic shape-changing feedback. Mechanotactile shape-perception is a frequently encountered natural and unobtrusive information channel [11]–[13] with properties that lead us to consider it to not have the distracting properties of visual, audio or vibratory feedback [14]. The Animotus was designed to be useful to both VI and sighted users and has since been demonstrated as effective for practical outdoor navigation assistance [15].

As users were guided through the Flatland space by the Animotus, they gradually uncovered the plot of the production via location-specific audio narration and large interactive tactile set pieces (Fig. 2). This plot was a non-linear contemporary adaptation of the original 1884 Flatland novel [1]. The pitch black environment placed both sighted and VI audiences in unfamiliar navigational territory, as sighted users could not navigate by vision and VI users could not rely on a cane, dog or other common tools. A goal of this being to ‘level the sensory playing field’ through which the production was experienced.

While many navigational devices are tested with limited numbers of VI persons, Flatland provided a unique opportunity for studying how relatively large number of vision impaired and sighted users navigated with the Animotus in an unfamiliar 112m^2 dark space. In this paper we will primarily focus on this navigational aspect of Flatland, which is also unusual in its ‘in-the-wild’ theatre approach. In addition to quantitative analysis of navigation data, qualitative analysis of audience interviews (recorded after the Flatland event) are also provided. This paper is an extension of an initial ‘work-in-progress’ extended abstract presented shortly after the completion of the production [16].

II. Related Work

Before presenting the method and results of our work, we will first review related work in inclusive immersive theatre, and navigation technology while also discussing navigation by VI and sighted persons.

A. Immersive and Inclusive Theatre Experiences

In the typical arrangement of a theatre or cinema, seats face a stage to focus audience attention on visual aspects of storytelling, creating a passive and largely inaccessible experience for blind spectators. Conversely, exploration of a performance space by an audience is synonymous with immersive theatre experiences, in which the plot is often spatially distributed through actors, props and events.

PunchDrunk, a leading immersive theatre company, creates sprawling ‘theatrescapes’ on an epic scale, with large buildings filled with elaborate set pieces and numerous actors [17]. However, the strong visual components of their work (e.g. dramatic lighting, choreographed dancing/fighting) and complex physical environments mean that a sighted guide is required to provide audio descriptions and navigation assistance to VI attendees (as observed from personal experience of the VI authors). Though there has been an ongoing trend of performance companies exploring immersive pitch-black spaces (e.g. Tutto Benne, David Rosenberg/Fuel, Sound&Fury, Sensory Labyrinth Theatre, etc.) accessible engagement considerations have not been a core motivator of these works. Additionally, ambulatory guidance in the space is typically provided by a human crew member or, in the case of Anagram’s ‘Door into the Dark’ [18], a length of rope, which is followed like a bannister and does not provide an opportunity for wandering.

Though there are a number of disability-led theatre companies, few have explored darkness for story-telling. An exception being Na Laga’at [19], who feature dark elements in performances from their deaf-blind cast, which target sighted and VI audiences. Our use of guidance technology in the dark permits audiences to retain their independence, in comparison to relying on a human guide.

We initially explored a combination of darkness, immersive theater and navigation technology in 2010’s production ‘The Question’ [20]. In that work, the 1DOF shape-changing Haptic Lotus device utilized a simple potential-field based ‘hotter/colder’ proximity based navigation scheme to guide users to regions of looping audio. Rudimentary localization and limited haptic feedback resolution restricted navigational and storytelling capabilities [21], though we later demonstrated that 1DOF feedback could be used effectively for navigation [22]. Flatland implements numerous technical elements to improve performance over The Question, regarding localization resolution, user co-ordination, user-centric audio triggering and haptic feedback. Additionally, more in-depth set design and narrative script was realized in Flatland, which also made use of a larger performance space with less obstructions. In both The Question and Flatland only 1 or 2 live actors interact with the audience, with all other dialog and sound effects pre-recorded in a studio.

B. Navigation Technology

The use of technology to aid navigation and wayfinding for pedestrians and vehicles has been a long-term research goal. A major achievement of these investigations has been the ubiquitous adoption of GPS enabled smartphones for pedestrian and vehicular navigation in various environments. However, the reliance of such systems on visual displays has led to concerns of distraction from environmental stimulus [23], [24], as reflected in increasing hospital reports to this effect as phones users neglect to pay sufficient attention to their surroundings [7]–[10]. Though audio cues provide a viable alternative to visual displays, these can also obscure useful environmental sounds when used with headphones, as is necessary in many urban environments [6], [25]. For vision impaired persons, screens are inaccessible and headphones can limit the ability of users to notice audible hazards, appreciate their surroundings localize using landmarks (such as a fountain or busy intersection) or be socially engaged with others [26]–[28]. For deafblind individuals, both visual and audio interfaces are inaccessible.

Conversely, the sense of touch is relatively unused while walking, making it an ideal channel for communication of simple instructions. Indeed, the most widely used navigation assistance tools for VI persons (the guide-dog and guide-cane) are essentially haptic interfaces, providing mechanotactile feedback to the user's hand via the cane's handle or dog's harness.

The concept of using haptic stimulus to aid navigation for VI persons has been explored for many decades, with regard to both wayfinding and obstacle avoidance [4], [5], [25] (note that our work only concerns wayfinding). However, as stated in [29], vibrotactile feedback has dominated haptic sensory substitution in guidance research (e.g. [3], [26], [27], [30]–[40]). Despite continuing investigation in this area (e.g. [38], [41]) few commercial solutions have resulted to practically benefit VI individuals. Indeed, the most successful application of vibrotactile feedback has been in providing discrete notifications in cell phones. Such stimuli are regarded as 'alerts' in [29], [42], due to their attention grabbing nature, which is well suited to notifying of an incoming call or message that must be answered. Though alerts are suitable for immediate hazard avoidance in navigation [30], this form of communication is unlikely to be appropriate for all forms of data conveyance [29], [43], [44], such as frequent correctional updates in motion guidance, which may extend over lengthy periods. As Zheng et al. point out, a stimulus with constant urgency is likely to distract from other ambient information [44]. Indeed, in several navigation studies, vibrotactile feedback has been noted to become annoying and impairing concentration after some time [15], [34].

Contrary to high-amplitude vibration produced by vibrotactors, shape and volume perception are innate human sensory abilities encountered frequently in daily life [11]–[13]. It is our hypothesis that a device that makes use of such modalities will provide a more subtle interface that falls within a more appropriate region of the attention spectrum [43] for the application of guiding without obscuring or distracting from environmental stimulus.

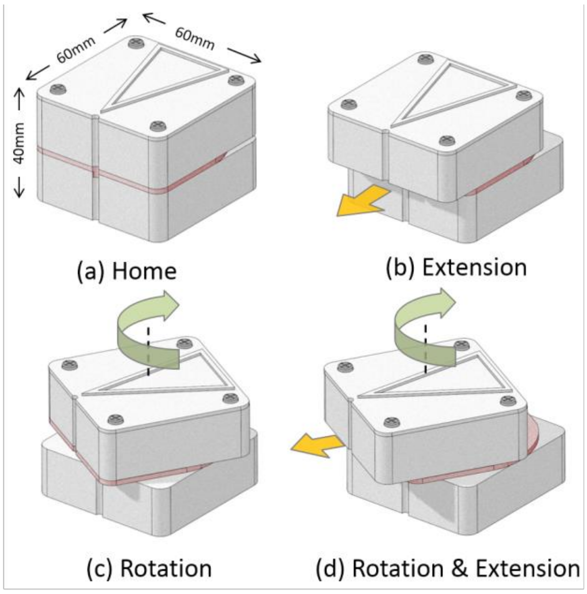

Fig 3: The Animotus is able to independently rotate and extend the upper part of its body to provide heading and distance to navigational targets or waypoints

Though several shape changing interfaces are present in past literature, many of these aim only for visual data representation and lack the force capability and mechanical robustness for haptic feedback and interaction [45]–[47]. While tactile shape displays may modify the shape of a single plane for haptic feedback, the volume of the drive mechanism often exceeds the workspace of the active surface by several factors [48]–[50]. A notable series of shape changing prototype interfaces by Hemmert et al. communicate via body tapering or thickness change in a mobile phone, as a method of communicating information [23], [51], [52]. Despite the intended application area of navigation, Hemmert's prototypes were only tested in simulated trials, with sighted users rotating an office chair in response to visual commands, but not actually walking/moving in a space. We feel that embodied navigation is necessary for true evaluation of such devices, with audience guidance being a necessary function of our system in the Flatland production.

Note that a more comprehensive review of the wide variety of navigational interface technologies, and their consideration in our development of shape changing interfaces, is discussed in [14].

C. Navigation by VI and Sighted persons

The self-localization and navigational abilities of humans and other mammals is an extensive research topic that dates back to the 19th century [53] and continues to be addressed in fields including neuroscience [53], [54], experimental psychology [55] and cognitive science [56]. Such investigations have naturally extended into comparing methods of representing and negotiating space between VI and sighted persons (e.g. [2], [28], [57]). However, the in-depth review of [56] claims that more recently this field has become fragmented, with opposing and contradictory views on key concepts. This variation in opinions, combined with the multi-faceted nature of the problem, makes designing a common interface for the needs of both VI and sighted persons challenging.

In [2], Loomis et al. state that VI individuals are at a 'considerable disadvantage' during 'regular navigation', due to absent visual information normally used to provide position and velocity information about the traveler's motion and the layout of near and far objects. It has also been questioned whether congenital or early blind individuals may be at a further disadvantage, as past visual experience may be necessary for the development of particular spatial abilities [55], [58]. Though a number of tests of various navigation and locomotion tasks have often shown equal performance by congenitally blind, late-VI and blindfolded sighted individuals (e.g. [2], [55], [59]), other studies have found congenitally or early-blind individuals perform less well than others on spatial tasks [55].

In addition to these more fundamental investigations, the study in [5] noted that wayfinding directions provided by VI or sighted participants can be difficult to interpret by someone from the opposing group. This is due to individuals focusing on different environmental or perceptual information, depending on their sensory abilities. This perceptual distinction also extends to recorded differences in navigation and exploration strategies between VI and blindfolded sighted individuals in unknown spaces [2]. In our work we have aimed to provide navigational guidance via our device, which should negate the requirement for such search strategies or dependence on environmental stimulus (of which there are few in Flatland).

III. Implementation

In this section we shall discuss the details of the Animotus navigation device and Flatland Environment.

A. The Animotus

To facilitate an appropriate method of exploration and guided navigation for immersive theatre scenarios, a unique navigation device, The Animotus (Fig 1 and 3) was developed. This handheld system modifies the shape of its body in order to communicate the direction and distance to the next location ('zone') that the user must walk to in order to progress through the physical space and narrative of Flatland. The shape-changing interface not only leaves the ears free to listen to recorded audio narration and sound effects, but also aims to be less cognitively obtrusive and distracting than more typical vibration-based haptic stimulation. Aside from Flatland, the navigation capability of the Animotus was evaluated by Spiers et al. in an indoor laboratory environment [14], [61] and unstructured outdoor urban spaces with sighted participants [15] (where navigational targets were waypoints on a longer path). These tests have shown the device to have potential as a general pedestrian navigation tool that minimizes both visual and audio distractions from environmental hazards and stimulus, compared to conventional smartphone interfaces.

The Animotus is a cube shaped device designed to fit comfortably in an adult hand (Fig 1). The device is able to extend and rotate its top half to respectively communicate distance and heading to a navigational target or waypoint (Fig 3). The cube-like 'home' shape makes shape-change perturbations easy to detect without resorting to exploration of the device via the user's fingers. The Animotus updates its shape continuously as the user navigates within an environment (as opposed to giving discrete turning cues). The design and function of the Animotus, in addition to technical specifics is described fully by Spiers and Dollar in [14], though a brief overview is provided here.

The linear DOF of the Animotus can extend by a maximum of 12.5mm. The extension of the Animotus *(E)* is proportional to the current distance from the user to the next target *(P)*. The maximum value of P to produce saturation (P_{max}) may be set dynamically for different environments and/or temporary scenarios. For the Flatland space this was set to 7.12m, following trial and error in pilot studies. In past laboratory studies, in smaller and more structured environments with single users, lower values of P_{max} were used.

Rotation of the top half of the Animotus corresponds to the heading to the next target. Within the mechanical bounds of ±30deg, the Animotus points directly at the target, providing fine heading feedback. If the heading to the target is outside of the range of ±30deg (for example, if the user needs to turn 60deg to face the target) then the rotational DOF will remain at either +30deg or -30deg, providing gross heading feedback. Such gross feedback informs the user to keep turning clockwise or counterclockwise (whichever is closest to the target heading) until they are in the range of fine feedback. The gross heading will change sign when the error passes 180deg.

Both Animotus DOF are driven by Hi-Tec HS-85MG servomotors with 3D printed transmissions integrated into the device body, as described in [14]. These actuators provide a good balance of torque, size, power consumption, cost and robustness, while not relying on external driver circuits as in other devices. An additional design precaution was that, if necessary, malfunctioning actuators could be quickly replaced and calibrated, in the interval between Flatland performances. Though this requirement was met, no failures occurred during any of the performances.

Several tactile features aid with aligning the Animotus in the hand and perception of the device pose. An embossed triangle on the top of the device helps users to non-visually identify the top and front of the cube when it is picked up. A 3mm groove that traverses the front face of the device to aid orientation and heading perception, by aligning across the top and bottom sections when the heading error is 0deg.

In our previous production, 'The Question' [62], the Haptic Lotus navigation device was attached to one of the user's hands with an elastic strap. This led to complaints from the audience that they could not use that hand for other tasks, and suffered fatigue from constantly carrying the device. As such, straps were deliberately avoided with the Animotus, with the tactile landmarks instead providing easy hand alignment cues. In Flatland, participants stored the Animotus in pockets when not in use [16], similar to a mobile phone.

In each Flatland performance, four participants simultaneously used one Animotus each to navigate the space. Each Animotus is equipped with an X-OSC Wi-Fi module [63], allowing continuous 100Hz updates from the navigation system.

B. Navigation System

Navigation with the Animotus in the context of Flatland relied on localization of audience members within the Flatland space, in addition to a pre-defined map of target locations (Fig 4). A Ubisense Ultrawide-band localization system with 4 sensors (placed in the corners of the workspace) tracked the position of active radio Ubitags (weight 40g, size 30x30x15mm), attached to one shoulder of specially designed overalls which the audience wore (Fig 1). The overalls were motived by a combination of artistic goals, pockets for device storage and necessity to keep participants warm in the insufficiently heated space during winter. The Ubisense system does not provide orientation feedback, so an IMU with integrated magnetometer (Adafruit 9DOF IMU) was used to create a complementary, tilt-compensated compass, which was worn like a watch on the wrist on the arm holding the Animotus. Localization accuracy of individuals was therefore established at 0.4m/2deg, which is relatively accurate for a non-empty, multi-user indoor workspace of this size (16x7m).

Data from the location and orientation systems was transmitted at 100Hz to a laptop PC running custom navigation software, written in the language Processing (www.processing.org). This software also stored the map of the environment with zone entrances and exits (Fig 4). During the production, the theatre crew used the software's GUI to monitor user positions in the dark space and assign each user (named 1-4) to a zone (named A-D) at appropriate times. Though the assigning of users to zones could have been automated, it was decided that human operators could better handle unexpected situations (such as equipment failures or users re-entering the same zone) in this untested experimental production. Following user/zone assignment, closed loop navigation was autonomously provided by the navigation software to each Animotus via a Wi-Fi link. The theatre crew also used the navigation software GUI to trigger audio in the headphones of users, to coincide with their progress through the space and narrative.

Note that the Animotus updates both its distance and proximity feedback continuously when activated, in response to real-time user position relative to the current target zone. This is opposed to other pedestrian navigation systems (such as Google Maps) that can be set to give discrete commands such as 'turn left' when navigating.

C. Environment

The Flatland environment was purpose-built for the production, within a former church, located in London, UK (Fig 4). The production space consisted of a 16x7m room in which window blackout panels had been installed for complete darkness. Night vision googles was used by sighted members of the production team for audience safety monitoring.

In the production space four target 'zones' were created, consisting of large tactile set pieces corresponding to an appropriate scene from the production's adaptation of Flatland (Fig 4). These scenes were pre-recorded as audio tracks by

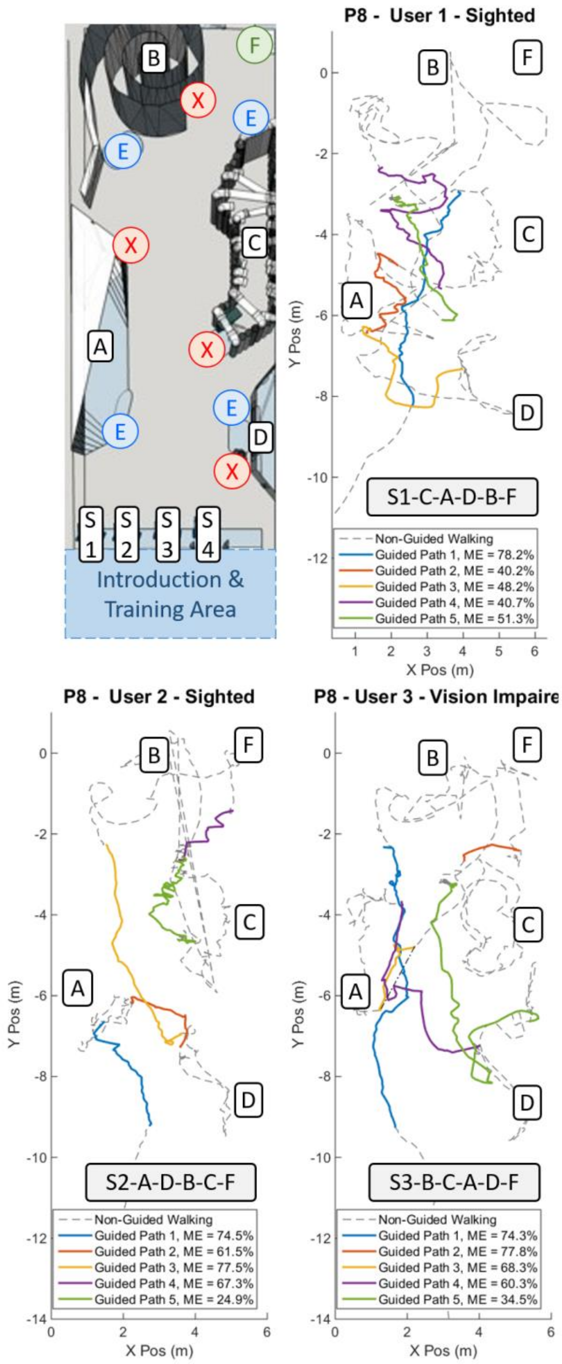

Fig 5: Paths from two sighted and one VI (bottom right) users during the same performance (P8). Solid lines show when guidance was provided by the Animotus, dashed lines show when users were inside target zones. A map of the environment and landmark markers (A-D) are shown in the top left in addition to start (S) and finish (F) locations (entrances and exit). Note that users enter through different doors (S1-S4). The intended motion sequence for each user is shown in the grey boxes. The mean path efficiencies of the 3 participants are 56.12%, 56.88% and 78.2% respectively. The mean walking velocities were 1.22ms, 1.61ms and 1.21ms,

professional actors/sound designers and delivered by wireless bone-conducting Bluetooth headsets to users as they entered each specific zone. Bone conducting headphones transmit audio while leaving the ears uncovered, allowing perception of an

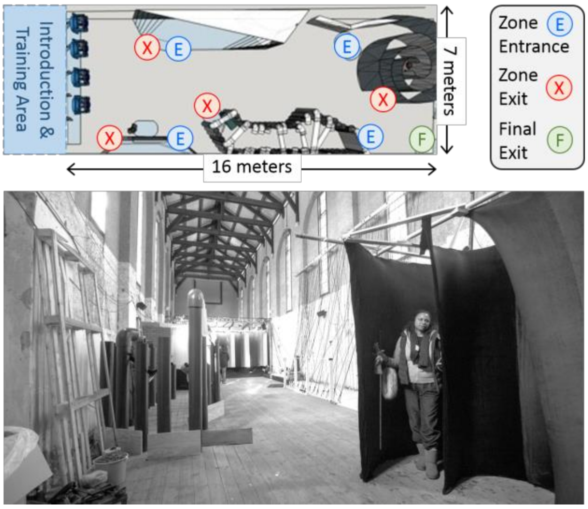

Fig 4: The Flatland environment layout (top). The photograph (bottom) was taken from point 'F' the map during construction. Three of the zones and entrance corridors are shown in the picture.

atmospheric ambient soundtrack delivered through speakers and occasional dialog from a live actor.

The tactile set pieces consisted of a large spiral corridor made of stretched cloth, a network of sound emitting plumbing pipes forming a walkway/corridor, the door, window and walls of a house and a corridor of ropes. Some set pieces are partially shown in Figs 2 and 4. The location and structure of the zones was not known to audience members before entering the space and it was the goal of the Animotus to guide audience members from the exit of one zone to the entrance of another, so that each audience member would visit each zone once. When an audience member reached a zone, the Animotus automatically assumed a home pose (a cube), then deactivated. At this point the user would be informed via audio that the Animotus could be stored in a pocket attached to the user's clothes, freeing up both hands for exploration. The zones/set pieces were self-contained areas designed for safe interaction in the dark. In addition, the guidance provided by the four Animotus devices were coordinated so that no more than one person would be in a zone at a time.

When the user left the zone (after the audio scene had finished) the Animotus re-activated to guide them to the next zone.

Four audience members at a time first entered a lighted 'Introduction and Training Area' before the performance. Here, an actor (in the character of an eccentric scientist) played the first scene of the narrative and explained the guidance function of the Animotus. Unfortunately, the Ubisense localization system's workspace could not be extended into the training area without significant loss of accuracy across the rest of the workspace (due to interference from structural elements in that part of the building). As such, an intended 'live' closed loop demonstration of the Animotus (in which it would respond to individual user motion as they moved relative to a training target) was not possible. Instead, all four audience members were requested to step and turn in different directions as their Animotus were simultaneously remotely controlled by a human theatre technician.

A total of 28 performances were completed, or which 12 involved no VI participants, 13 involved 1 VI participant and 3 involved 2 VI participants.

Each performance lasted 40 minutes and ended with all users being guided to an exit, where their Animotus were removed while still in the dark. A sound simulating the device being crushed was played as a plot climax. Following this, audience members were guided to a seated area and interviews took place.

D. *Narrative*

Our adaptation of Flatland puts the audience in the perspective of a tourist who is being introduced to the Flatland world by the original novel's protagonist, the 'elder square' (played by a live actor). This character provides each audience member with an Animotus as their guide. By visiting the zones the audience learns that the land is dystopian, other worlds of higher and lower dimensions exist and that the elder square is being pursued by guards of the king of Flatland. The play ends with the guards catching up with the audience and the Elder Square.

IV. Motion Evaluation

As each audience members navigated the Flatland space, their position and orientation co-ordinates were logged by the navigation PC, along with current target locations. From this data, measures of motion efficiency, average velocity, the time that users faced their current target and rates of improvement were all determined. We have used measures of motion efficiency, average walking velocity and time facing the target in past work to compare Animotus performance against other haptic navigation devices [14], [15], [64]. Note that there are no standardized metrics for evaluating navigation ability with tools such as the Animotus. In fact, many related works in this area do not evaluate their devices in embodied walking experiments, instead keeping their users stationary or able only to rotate on the spot [23], [34], [36], [40], [41]. Several past works have made use of walking speed as a measure of navigational ability [65]–[67], where a speed close to typical rates is desirable. Though some work has looked at time to complete a given course [30], [34], we do not believe this metric is appropriate to Flatland, where participants are appreciating an immersive theatre production of a set length and so are not rushing to reach all target zones. Note that [67], [68] included bespoke metrics related to efficiency.

User walking motion was regarded in terms of 'paths', which are walking trajectories between zones, guided by the Animotus. Generally 5 paths were logged for each user, consisting of 1 path per target and a final path to the exit, though some users missed some zones.

Fig 5 illustrates the paths for sighted and VI audience members during the 8th performance of Flatland. User exploration within the zones/set pieces (when the Animotus is deactivated) is illustrated with dashed lines and labelled as 'Non-Guided Walking'. These motions were not analyzed. Participants within the same performance visited the set pieces in different orders. As can be noted from Fig 5, detours often occurred in the paths. User path plots from 3 additional performances (giving a total of 12 participants) are included in the supplemental material of this manuscript.

A. Motion Metrics

In order to measure motion efficiency *(ME)*, user path lengths were compared to a virtual straight line trajectory between first and last point on the path:

$$ME(\%) = \frac{E_P}{U_P} \tag{1}$$

Where E_P is the Euclidean distance between the start and end of the motion (the optimal path), U_P is the distance covered by the user's path and *ME* is the resulting path efficiency ratio. User path length (U_P) was calculated as the sum of Euclidean distances between successive positions (X_i, Y_i) and (X_{i+1}, Y_{i+1}) in the position log, as follows:

$$U_P = \sum_{i=0}^{n} \sqrt{|X_i - X_{i+1}|^2 + |Y_i - Y_{i+1}|^2} \tag{2}$$

From the time taken to complete each path and UP, the average walking velocity *(AV)* was also determined.

The Proportion of Time Facing the Target (T_{FT}) was also calculated to identify different user movement strategies and walking heading accuracy. This was measured by counting the number of logged time steps when participants faced the current target (within ±5, ±10, ±20 and ±30 degrees) and dividing by total number of logged time steps for that path. Fine heading feedback is provided within ±30 degrees by the Animotus (Section 3.1).

V. Results

94 audience members took part in Flatland, 15 of whom were VI. The smaller group number for VI persons is largely based on the relative proportion of VI to sighted persons in London,

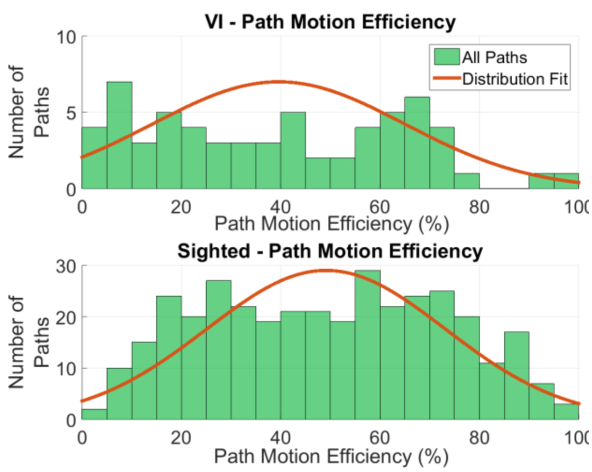

Fig 7: Histogram showing the distribution of motion efficiency (ME) for all paths in the VI and sighted groups.

where the study was held. When receiving requests to attend the performances (which were free of charge), VI persons were given priority over sighted persons to attempt to increase VI numbers.

The log files of two sighted attendees were partially corrupt and could not be used for motion metric analysis, apart from the number of zones visited. One blind user deliberately ignored the Animotus and target zones during the performance, stating in a later interview that they "wanted to take advantage of the rare chance to walk unassisted". Their results were also not included in the numerical analysis. Following these considerations, 77 sighted and 14 VI participants contributed to the majority of the navigational data set.

A. Quantitative Motion Performance

1) Targets Visited

The number of target zones visited by audience members is illustrated in Table I. Though the table shows the VI group as somewhat more likely to miss target zones, it should be noted that the sample size is smaller.

TABLE I
Number of Zones Visited By Audience Members

With Outlier Removed	Located All Zones	Missed 1 Zone	Missed >1 Zones
Sighted n = 79 (% of Sighted)	66 (83.55%)	9 (11.4%)	4 (5.06%)
V.I n = 14 (% of VI)	11 (78.57%)	2 (14.29%)	1 (7.14%)
Total n = 93 (% of Total)	77 (82.8%)	11 (11.82%)	5 (5.38%)

2) Motion Efficiency

Motion efficiency distribution of all participants is presented via boxplots in Fig 6, grouped into VI and sighted individuals and sorted by the median value for clarity. In all cases, all of a participant's walking paths with the Animotus contributed to the boxplot. This led to a data set with 358 walking paths for the sighted group and 63 walking paths for the VI group. An unpaired t-test illustrates significant differences in efficiency between these groups *($p = 0.0041$)* with an observed effect size of *Cohen's $d = 0.377$*. The mean motion efficiency of sighted participants is 9.5% higher than VI participants (49.1% and 39.6% respectively). This may be because the initial introduction / training with the Animotus was completed in a lighted area – though efforts were made to focus on tactile rather than visual features. It is notable that for 5 VI users (35.7% of the group) all efficiency results were lower than the group mean. This is in comparison to only 4 sighted users (5.2% of the group). Individual user result distribution gives mean standard deviation (SD) for sighted as 21.89% vs. 20.49% for VI, indicating a 1.4% increase in consistency in walking efficiency for VI users.

Fig 7 displays the same data in histogram format with a fitted normal distribution. Sighted distribution appears more unimodal than VI participants, but this may be an effect of higher sample numbers.

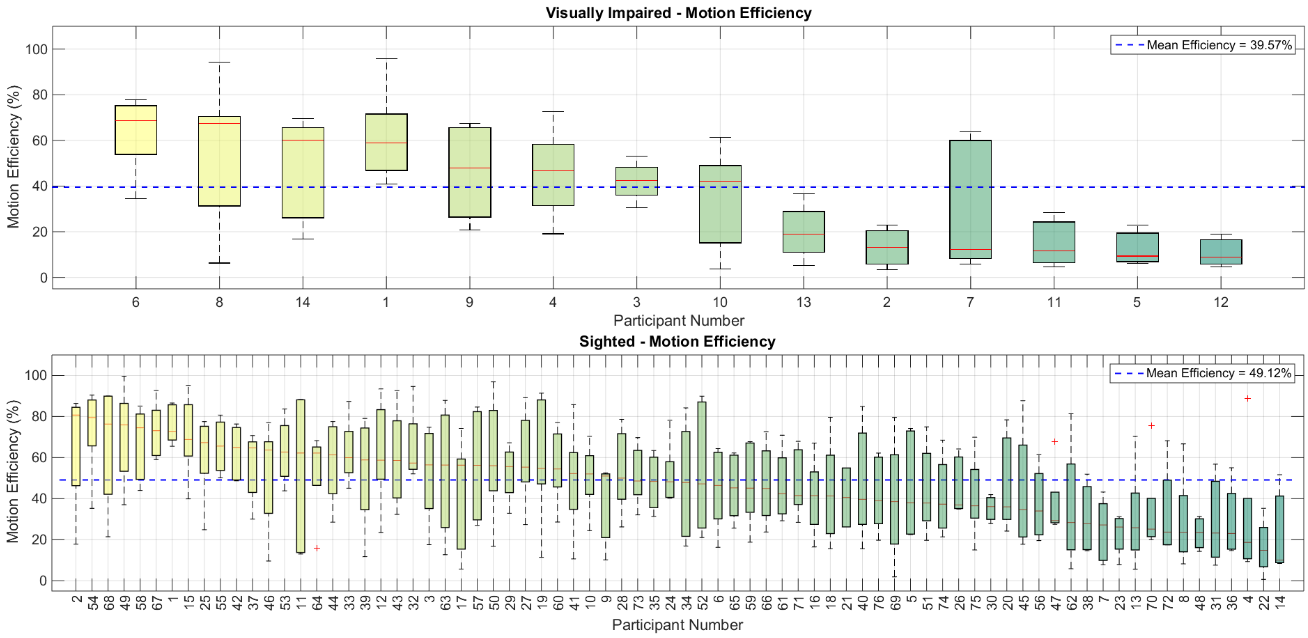

Fig 6: Movement Efficiency (ME) of Vision Impaired (Top) and Sighted (Bottom) audience members, considering all walking paths guided by the Animotus (Fig 5), sorted by median value.

3) Efficiency Improvement

The mean rate of efficiency improvement was determined by fitting a linear function to the efficiency results of the individually walked paths (in chronological order) and taking the overall gradient. The result for VI persons was 0.95% compared to 0.05% for sighted users. The <1% values indicate that improvement was negligible. This is unsurprising, given that participants only walked five paths and were involved in a theatre experience, meaning their attention should have been on the environment, set and narrative. This is in comparison to a lab experiment, where clear navigation tasks are presented in a controlled environment. An unpaired t-test demonstrated that there was no significant difference between VI and sighted groups *(p=0.8107)* with effect size of *Cohen's d = 0.135*.

4) User Velocity

Boxplots of user walking velocity (recorded only during Animotus use) are illustrated in Fig 8 and Fig 9. The mean velocity between sighted and VI audience members was similar, with sighted users walking at 1.10m/s and VI users walking at 1.12m/s (a 2% difference). These values are both similar to the typical 1.4m/s walking pace of a sighted human [69], indicating only a minor speed reduction when using the device. An unpaired t-test demonstrated that differences in walking velocities were not statistically significant between the two groups *(p = 0.138)* with effect size of *Cohen's d = 0.212*. Again, average individual standard deviation was similar, with sighted SD = 0.40 m/s, and VI = 0.39 m/s. It is notable that the proportion of users below the average for each group was more similar in velocity than efficiency with 28.57% of VI users vs. 23.08% of sighted users.

5) Proportion of Time Facing Targets

Fig 10 illustrates the proportion of time that participants faced the target while navigating a path, within bounds of ±5, ±10, ±20 and ±30 deg. It appears that distribution of results is greater for the sighted group, with a higher median value in most cases. Both groups were within the ±30deg for over 75% of time (median value), implying that the gross / fine heading feedback distinction was effective, though fewer participants were able to directly follow the feedback to be within 5deg.

VI. Audience Interviews

Loosely guided group interviews were conducted with audience members immediately after each performance. The interviews lasted 40-45 minutes and provided a wide range of reactions, with many participants providing more emotional responses than encountered during laboratory based studies with the same technology [14]. An in-depth thematic analysis of the transcribed interview data was carried out as an iterative process that took several months using the NVivo tool (QSR International Pty Ltd). Through this process a number of themes emerged and were agreed upon. In [70] we discuss the theme of control with regard to the device and production as a whole, i.e. whether the users felt they were being controlled by the technology or were in control of their experience. This was considered during different stages of the production, such as when the Animotus was not in use (during exploration of the zones). Here, we discuss the themes related to participants' response to the Animotus, and their understanding of the way the technology worked. These are primarily considered in terms of device design evaluation. As such many of the following observations and quotes did not feature in [70]. When necessary, we use the notation {S} or {V} next to a quote to indicate if the speaker was sighted or visually impaired.

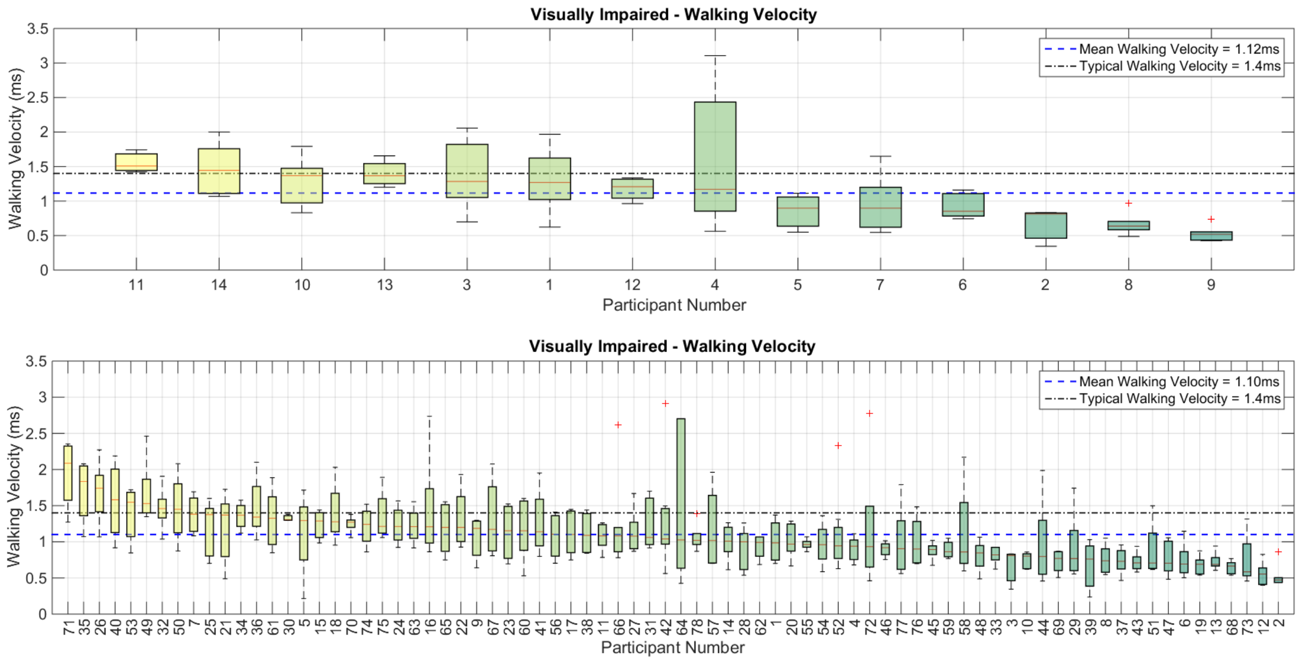

Fig 8: Walking velocity of VI and sighted participants while guided by the Animotus. The average velocity of VI participants is 1.12ms, while sighted persons walked at 1.1ms. Typical walking pace of sighted humans is 1.4ms.

A. *Reliance*

Opinions of the Flatland production and the Animotus varied across both VI and sighted individuals. It was noticeable that fifteen sighted persons stated that they relied heavily on the device when in the dark, citing a *"sense of security"* given by the Animotus to counteract *"sensory deprivation"* of the dark environment, which some found *"oppressive"*. One participant went as far to say *"I don't think I could have gone anywhere at all without [the Animotus]"* {S}. Conversely, a VI participant commented that *"being in the dark and not able to find their way [was] quite a familiar situation"*. However, another VI participant stated that *"because I use a white cane, I'm feeling with my right hand all the time. It feels hard to break that habit"*. Participants expressed different views on their relying on the device, with sighted participants being clear that they felt the need for the device, but VI participants discussing more varied ways of moving around.

B. *Technological Concerns*

It was noted that participants became *"worried"* or assumed the Animotus was *"broken"*, if it didn't act as they expected. These expectations were sometimes incorrect. In particular, six individuals commented that they lost faith in the Animotus when it didn't alert them to the presence of nearby obstacles, including other audience members (as a white cane would). In fact, the device functions more like a smartphone GPS navigation system, by providing a walking path between two locations, and not considering local obstacles. It was also clear from interviews that some individuals did not understand how to interpret the haptic stimulus provided by the device, leading to collisions as they focused on unimportant tactile features. Eleven (both VI and sighted) participants stated they were

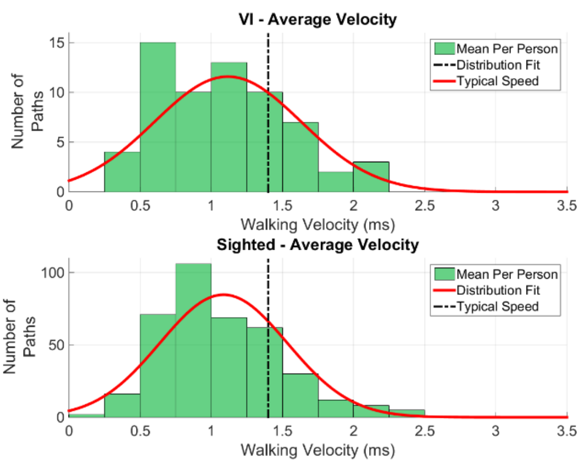

Fig 9: Distribution of walking speed across all paths

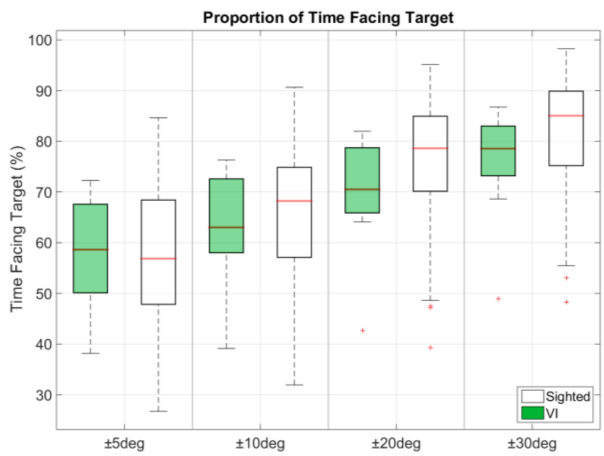

Fig 10: Distribution of the proportion of time facing the target during navigation, within various ranges

unsure of the *"rules"* of the environment, while sixteen users stated they were at times unsure how they should have held the Animotus and explained interpretation of the device stimulus in ways that were incorrect. For VI participants some of this confusion may be due to unintentional visual clues during training that may have aided sighted participants. Unfortunately video recording of the performances malfunctioned, so how users held the devices could not be determined after the event. A more thorough familiarization / training exercise and introductory dialog could reduce these issues.

Other feedback demonstrated different responses to technical issues in a cultural scenario. Two sighted persons in the same performance had different reactions to a temporary lag in Animotus response. Participant 1 stated *"It didn't quite work, so I gave up with it"*. Participant 2 however stated *"I just decided, 'Well, I will give it a bit of time'"*. This patience was rewarded as she later described the system as "*delightfully simple […] I didn't have to worry about the device, and I could concentrate on thinking about my environment, and following it"*. A similar feeling of intuitiveness was described by a blind audience member – *"I wasn't consciously thinking, "I turn right or turn left". I just thought, 'Go with the flow.'"*. No audience members described the feedback method as annoying, which has previously been reported after extended use of vibrotactile guidance systems [15], [34]. Interestingly, five users talked of other vibrating technologies they had encountered, showing the proliferation of such haptic feedback.

C. Engagement

Regarding engagement with the Animotus, there was a distinction on whether the device was regarded as a machine (*"it's just like, yet another tool to navigate"* {VI}), anthropomorphized into a character (*"I felt like it had a bit of sentience to it"* {S} / "I thought it was my little demon" {S}), or integrated into the users body (*"It sort of became really part of me"* {S}). Twenty-seven participants used terms such as *'pet', 'friend'* and *'companion'* with endearing adjectives such as *"sweet"* and *"cute"*. One user stated *"[the] reasonable side of me knows it's a lot of electronics but […] I felt sympathy with it [it was] my pet, my baby […] I should protect it"* {VI}. Six users described strong emotions of *"upset"* were attached to the removal and simulated destruction of the *"vulnerable"* device at the end of the performance: *"I can't believe they took it away […] I definitely saw it as something that was helping me"* {S}. Some users did not instill characterful traits into the device yet still regarded it favorably *"it was very much a tech piece for me and I was like, 'How's it doing that? How's it tracking us, I think that's, like, amazing'"* {VI} and *"I didn't see it, really, as an animate thing, but I still saw it as a companion of some kind"* {S}. Others felt less positively after struggling to navigate *"I really disliked mine a lot"* {S}. Certainly, the device engaged many and functioned well for many individuals, serving a guidance role as intended *"[I] depended on it and saw it as a guide rather than a gadget"* {S}.

Interestingly, some users resented the guidance and assumed the device was being remotely piloted by a human "*[It] connected us to someone who was showing us where to go*", *"I knew someone was directing me"* {S}. Though the device was in fact autonomous, it is interesting to note the hostility directed here to non-autonomous assumptions.

Finally, the practice of designing the experience and navigation system simultaneously appeared to pay off from an experience perspective, based on this user's testimonial *"But it felt right. Like it fitted into the story and it looked right and it felt right with respect to the whole narrative"* {S}. We can assume that even if not all participants (VI or sighted) had felt the need to rely on the Animotus, the experience of using the device had been interesting and engaging.

VII. Conclusion

The experimental theatre production Flatland aimed to investigate the potential of equivalent, inclusive experiences for sighted and VI audiences. Central to this was the notion of a guiding technology though an immersive dark environment that would be useful to both blind and sighted individuals. In this paper we have examined how the Animotus was used in the space by these audience groups.

Quantitative results indicated that sighted audiences walked marginally more efficiently with the Animotus than blind audiences, but were statistically equal in terms of change in efficiency, walking velocity, and number of target zones found. Qualitatively, broad opinions on usefulness and engagement were given on the Animotus, which appeared well balanced across members of the VI and sighted audiences. Confusion regarding how the Animotus should be held may be addressed by considering ergonomics in future devices that are designed to comfortably 'fit' into the hand in appropriate orientations.

It is clear that appropriate familiarization and training with the technology could improve perception of the device, as many negative comments stemmed from misperception of device function and capability. Indeed, the addition of 'training zones' for hands-on user familiarization would have likely cemented previously explained navigation concepts. This was the practice we adopted in previous studies [15], [71], but unfortunately were unable to implement in Flatland.

Further negative opinions stemmed from device malfunctions, which are largely inevitable from the initial attempt at a large scale *in-the-wild* experimental work of this nature. Specifically, uncertainty regarding whether the device was 'broken' is likely to have stemmed from latency in the indoor tracking system due to the cluttered environment. It is possible that device behaviors to indicate that it is waiting for location data (analogous to an online loading icon) may increase confidence by showing that the device is still active.

This initial work has demonstrated the potential of novel technology to enable engaging and emotional cultural works that cross boundaries of sensory ability to enable blind and sighted audiences to share experiences. Indeed, it is not obvious from individual user performance data or interview responses whether a responding audience member is sighted or VI, implying that some form of equivalence has been achieved. Though this form of performance is certainly esoteric, the increasing popularity and scale of general immersive theatre (such as *PunchDrunk's 'Sleep No More'* which has run for over

5 years in New York City) implies that fruition of such art forms are certainly possible.

VIII. Acknowledgements

We would like to acknowledge the extended Flatland production crew, which was made up of over 40 theatrical, creative and technical specialists (who were both blind and sighted). Names and roles of all persons involved may be found at *http://flatland.org.uk/about/project-team/*

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